Theoretical and Empirical Relationships Between Oat Test Weight and Groat Proportion

Douglas C. Doehlert,[1,2] Jae-Bom Ohm,[1] Michael S. McMullen,[3] Neil R. Riveland[4]

Cereal Chem. 86(2):239–246

ABSTRACT

Test weight and groat proportion are two very important quality characteristics of oat grain. In this study, we pose the hypothesis that these two characteristics are related through characteristics of grain density. Test weight is defined as the product of kernel density and packing proportion. Groat proportion, in theory, is the ratio of the groat mass to the kernel mass. We present two theoretical constructions expressing test weight in terms of groat proportion, packing proportion and kernel density components. To test these, we have applied measurements of test weight, groat proportion, kernel density components, and packing proportion of 18 oat cultivars grown at six environments. Whereas the groat proportion alone accounted for only 34% of the variation in test weight, our theoretical constructions that included groat proportion could account for ≤82% of variation in test weight. Also, we present previously undescribed variation in oat kernel density components across genotypes and environments. Although the kernel density alone could account for most of the variation in test weight across genotypes, packing proportion appeared to be more important in describing variation in test weight of a genotype across different environments. We observed significant variation in both groat and hull density which, together with groat proportion, described most of the variation in kernel density.

Test weight, or bulk density, is the mass of grain that fits into a specified volume. It is often considered to be one of the most important measures of grain quality (Stoa 1922; Sword 1949; Lea 1955; Hoffmann and Livezey 1987; Forsberg and Reeves 1992). It constitutes a characteristic of major importance in grain grading (USDA 1988) and remains an important characteristic considered in commercial grain purchases (Ganssmann and Vorwerch 1995), although historically its value has been disputed (Grieg and Findlay 1907; Zavitz 1927; Sword 1949; Peek and Poehlman 1949). It can be described as the product of mean kernel density and packing proportion (Hlynka and Bushuk 1959; Yamazaki and Briggle 1969; Doehlert and McMullen 2008)

$$TW = KD \times PP \quad (1)$$

where TW is test weight, KD is mean kernel density, and PP is packing proportion. Packing proportion is the proportion of the volume of a container that is actually occupied by the grain. In our earlier work (Doehlert and McMullen 2008), this value was called packing efficiency, and expressed as a percentage, but for the mathematical permutations to follow, it is necessary to express this as a proportion. Mean kernel density is kernel density based on the kernel envelope volume. The kernel envelope volume is the physical displacement of the oat kernel. It is as if a shrink wrap was placed around the kernel, the kernel envelope volume is the volume inside the shrink wrap. This laboratory has recently measured oat kernel density using sand displacement (Doehlert and McMullen 2008). Packing proportion was then derived from test weight and kernel density by a rearrangement of equation (1).

Groat proportion (GP), in theory, is the mass proportion of the groat to the whole oat kernel (with the hull), although measured GP values commonly depart significantly from this value

$$GP = GM/KM \quad (2)$$

where GM is the mean groat mass and KM is the mean kernel mass. Groat proportion is usually expressed as a percentage (GP × 100). Groat proportion has been considered by many to be a more important oat quality characteristic than test weight (Love et al 1925; Stoa et al 1936; Atkins 1943; Bartley and Weiss 1951). Because it is the groat that is of primary interest to commercial operations, groat proportion provides a more accurate estimation of the economic value of a sample of oat grain than does test weight. However, groat proportion is significantly more difficult to measure accurately (Doehlert et al 1999; Hall et al 2003). A number of studies have indicated significant correlations between test weight and groat percentage (Stoa et al 1936; Atkins 1943; Bartley and Weiss 1951; Pomeranz et al 1979; Doehlert et al 1999). However, these studies generally indicate that groat proportion can account for only about one half of the variation in test weight (Pomeranz et al 1979). Therefore, it appears that additional factors affect both test weight and groat proportion that cause the values to diverge.

Kernel density analysis allows us to derive precise theoretical mathematical relationships between these test weight and groat proportion. Mean kernel density is defined as

$$KD = KM/KV \quad (3)$$

where KV is the mean kernel envelope volume. If we rearrange equation (3) to solve for mean kernel mass, and then substitute into equation (2) we get

$$GP = GM/(KD \times KV) \quad (4)$$

We can rearrange equation (4) to express mean kernel density in terms of groat percentage

$$KD = GM/(GP \times KV) \quad (5)$$

We can now substitute mean kernel density into equation (1) to express test weight in terms of groat percentage

$$TW = (PP \times GM)/(GP \times KV) \quad (6)$$

Thus, a straightforward relationship between groat proportion and test weight can be easily derived. Although the relationships are not necessarily intuitive, these provide a solid theoretical basis for observed correlations. Also, the presence of multiple other factors in the relationships provides the bases for departures from more perfect correlations.

[1] USDA-ARS Hard Red Spring and Durum Wheat Quality Laboratory, Harris Hall, North Dakota State University, Dept. 7640, P.O. Box 6050, Fargo, ND 58108. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

[2] Corresponding author. Phone: 701-231-8069. E-mail: douglas.doehlert@ndsu.edu

[3] Dept. of Plant Sciences, North Dakota State University, Dept. 7640, P.O. Box 6050, Fargo, ND 58108.

[4] NDSU Williston Research Extension Center, 14120 Highway 2, Williston, ND 58801.

doi:10.1094/CCHEM-86-2-0239

An alternative approach to relate test weight and groat proportion can be devised if we assume that the mean kernel mass is equal to the sum of the mean groat mass and the mean hull mass (per kernel)

$$KM = GM + HM \tag{7}$$

where HM is the mean hull mass (per kernel) and that the mean kernel volume is equal to the sum of the mean groat volume and the mean hull volume

$$KV = GV + HV \tag{8}$$

where GV is mean groat volume and HV is mean hull volume (per kernel). Whereas, equation (7) is largely indisputable, equation (8) may not be entirely accurate. In previous studies from this laboratory (Doehlert and McMullen 2006, 2008), we considered the possibility that empty space may occur within the hulls. Although these previous studies failed to conclusively test that hypothesis, we cannot dismiss this possibility. However, because our current technology does not allow us to directly measure mean hull mass and volume per kernel with any reliability, we are forced to accept the assumptions in equations (7) and (8) to make any estimation of hull properties. Thus, we can express kernel density from a combination of equations (3), (7), and (8)

$$KD = (GM + HM)/(GV + HV) \tag{9}$$

Because GM = GP × KM (from equation 2) and HM = KM × (1 – GP) (from equations 2 and 7), then substituting for GM and HM in the numerator, we get

$$KD = [(KM \times GP) + KM(1 - GP)]/(GV + HV) \tag{10}$$

Because GV= GM/GD and HV= HM/HD, we can substitute in the denominator to get

$$KD = [(KM \times GP) + KM(1 - GP)]/[(GM/GD + HM/HD)] \tag{11}$$

Now, because GM = KM × GP and HM = (1 – GP) × KM, as indicated above, we can again substitute in the denominator to get

$$KD = [KM \times (GP + 1 - GP)]/[(KM \times GP/GD) + (KM \times \{1 - GP\}/HD)] \tag{12}$$

The value KM can cancel in the numerator and denominator, and because (GP + 1 – GP) = 1 we can simplify this expression to

$$KD = 1/[(GP/GD) + (1 - GP)/HD] \tag{13}$$

We can now substitute this expression for KD into equation (1) to get

$$TW = PP/[(GP/GD) + (1 - GP)/HD] \tag{14}$$

Equation (14) is perhaps a more intuitive expression of the test weight as a function of groat proportion, in that it includes densities of the constitutive parts of the oat kernel and the packing proportion.

In this study, we have measured test weight, groat proportion, packing proportion, and mass, volume and density of oat kernels groats and hulls from 18 genotypes grown at six different environments. We have applied these data to the theoretical constructs derived above, and to other theoretical constructs to test hypothesized relationships between test weight and groat percentage. We have also examined the variation of these characteristics across genotype and environment, and have analyzed other possible relationships among these characteristics.

MATERIALS AND METHODS

Plant Material

Eighteen oat (*Avena sativa* L.) cultivars (AC Assiniboia, Beach, Brawn, CDC Dancer, Gem, HiFi, Killdeer, Leonard, Maida, AC Morgan, Morton, Otana, AC Pinnacle, Ronald, Triple Crown, and CDC Weaver) and two breeding lines (ND021612, ND030291) were grown at three locations (Carrington, Fargo, and Williston) in North Dakota in 2005 and 2006. A seeding rate of 2.47×10^6 kernels/ha was used for all experiments. Herbicide treatments consisted of preemergence application of 3.93 kg/ha propchlor and postemergence application at the 3-leaf stage with a tank mix of 0.14 kg/ha thifensulfuron, 0.07 kg/ha tribenuron, and 0.14 kg/ha clopyralid. Experimental units consisted of four rows spaced 0.3 m apart and 2.4 m long. The two center rows were harvested with a two-row binder and threshed with a plot thresher. The harvested grain was cleaned using an office tester and cleaner (model 400, Clipper, Bluffton, IN) fitted with a 4.75 × 19 mm oblong hole sieve and with aspiration adjusted so that kernels containing a groat were not removed. The sieve removed grain that was <2 mm in width.

Test Weight and Groat Proportion

Test weight was determined by weighing a fixed volume of grain from a test weight filling hopper (Seedburo Equipment Company, Chicago, IL).

Groat proportion was determined by impact dehulling as described by Doehlert and Wiessenborn (2007). Samples (50 g) were placed in 450-mL glass jars. Grain moisture was determined by measuring the mass loss in a 2-g grain sample after 2 hr at 130°C in a convection oven. Moisture of grain was then adjusted to 9% by adding water to the grain in the jars, sealing for 24 hr, and shaking at intervals.

The North Dakota State University Agricultural and Biosystems Engineering Department manufactured the impact dehuller. It consisted of a 50-cm diameter, 12-vein rotor and a granite impact ring. Rotor speed was controlled with a variable frequency drive and calibrated with a tachometer. Rotor speed was set to 1,661 rpm for this study, which corresponded to a peripheral speed of 43.5 m/sec. Samples (50 g) equilibrated to 9% (db) moisture were poured by hand into the dehuller at a rate of ≈200 g/min. Dehulled samples were collected at the bottom of the dehuller. Free hulls were removed by initially passing the sample through a laboratory aspirator (Kice Metal Products, Wichita, KS), and afterward passing the sample through a Bates-type laboratory aspirator (Seedboro). Hulls were discarded without examination. Immediately after aspiration, the mass of the crude groat preparation was recorded and the sample was stored in paper envelopes until sorting. Moisture changes in the storage of the grain samples between the time of dehulling and sorting required that the mass of crude groat samples be measured again immediately before sorting. This allowed for the calculation of the moisture correction factor (MCF), which was the original sample mass divided by the current sample mass (Doehlert and McMullen 2001). Samples were then sorted by hand to remove broken groats and oats resistant to dehulling. Groat proportion was corrected for the hulled oats remaining after dehulling as

$$GP = \{[(G + B) \times MCF]/[WO - (R \times MCF)]\} \tag{15}$$

where WO is the whole oat mass, R is the mass of oats resistant to dehulling, G is the mass of unbroken groats, and B is the mass of broken groats. Only whole unbroken groats were used for groat size and density analysis.

Digital Image Analysis

Grain and groat linear measurements of length, width, and area were determined by digital image analysis as validated in detail in Doehlert et al (2004), with modifications as follows. Briefly, 10-g samples of either oat grains or groats were spread on the surface of a light box, next to a measuring stick. A digital photograph (5.2 megapixels) was taken with a digital camera (DSC-F707, Sony, Tokyo, Japan). Images were downloaded to a computer and edited with photo-editing software (PhotoShop, Adobe, San Jose, CA). The length scale was removed from images and pasted into a separate image for calibration. Images were converted to a gray scale and edited so that only kernels were present. Images were then analyzed with image analysis software (Aphilion, Amerinex Applied Imaging, Amherst, MA). A macro written for the program generated width, length and area measurements for each kernel in the image individually. Means of these values were used for analyses in this study.

Sand Displacement

Oat kernel and groat envelope volumes and densities were measured by sand displacement as originally described in Doehlert and McMullen (2008). Oat grain and groat samples of 25 g were used for volume analysis by sand displacement. Fine white silica sand was used for oat grain volume measurements. Sand purchased from a hardware store designed for sandblasting and sand collected from a beach (Siesta Beach, Sarasota FL) both proved satisfactory for the procedure. Sand was poured into a steel measuring cup with a volume of 118 mL. The cup was filled to overflowing with sand and then while grasped by the handle was tapped lightly against the bench for ≈20 sec to uniformly pack the sand. This packing procedure was necessary to obtain reproducible results. A straight-edge was then used to level the sand in the cup which was then emptied into a holding container, and the oat sample was introduced into the cup. Sand in the holding container was then introduced back into the measuring cup containing the oats until the cup was about half filled. The oats and the sand were then mixed thoroughly with a metal spatula to obtain complete contact of the sand with the oat grains and to eliminate air pockets. The remaining sand in the holding container was then introduced back into the cup with the oats. The cup containing the sand and oat mixture was then tapped again for 20 sec to obtain uniform packing. Excess sand was then leveled off from the cup with a straight-edge. The mass of the sand displaced in the cup by the oats was then measured. Grains were separated from the sand by hand sieving on 600 m*M* mesh sieves (U.S.A. Standard Testing Sieves, #35 Mesh, A.T.M., Milwaukee, WI). This procedure was repeated four times for each sample and the mean displaced sand mass was used for calculations.

The volume of the oats in the sample was obtained by dividing the mass of the displaced sand by the measured bulk density of the sand (1.65 g/cm^3).

The mean oat grain volume was obtained by dividing the volume of the oat sample by the number of grains in the sample. Mean grain volumes were converted to mm^3 (cm^3 × 1,000) for ease of calculation. The number of grains in the sample was obtained by physically counting grains by hand. Mean grain mass was obtained by dividing the sample mass by the number of grains in that sample. Mean grain density was obtained by dividing the mean grain mass by the mean grain volume.

Packing proportion was estimated from the ratio of test weight and grain density. It is necessary that test weight and grain density be in the same unit, although the units cancel in this calculation.

Groat volumes and densities were measured by the same procedure as were grain volumes and densities. Hull mass, volume, and density were determined indirectly because of the insurmountable problems involved in using sand displacement with light weight hulls. Hull mass was calculated as kernel mass minus groat mass. Hull volume was calculated as kernel volume minus groat volume. Hull density was calculated as hull mass divided by hull volume.

Weather Data

Weather data was gathered by automated weather stations located within 1,000 meters of the field plots. The stations were managed by North Dakota Agricultural Weather Network (NDAWN) and results were obtained online (http://ndawn.ndsu. nodak.edu). Weather data used for the analyses included monthly means of daily maximum air temperature, daily minimum air temperature, daily average air temperature, solar radiation, potential evapotranspiration and total monthly rainfall.

Experimental Design and Statistical Analysis

Field plots were arranged in a randomized complete block design with three replicates. Analysis of variance was applied to data where genotype and environment effects were considered random with PROC MIXED procedure with DDFM = KR option in a computer package (v.9.1, SAS Institute, Cary, NC). Analyses of variance were calculated where the environment × replicate mean square was used as an error term to test the environmental effect. The genotype × environment interaction mean square was used to test the genotypic effect, and the genotype × environment interaction was tested with the residual mean square. Genotypic and environmental means and genotypic means across environments were estimated by best linear unbiased prediction (BLUP), using the ESTIMATE statement in the PROC MIXED. Separation for BLUP of means of genotypes and environments were evaluated by the least significant difference, which were calculated by standard error and degree of freedom obtained by the ESTIMATE statement. Correlations for the entire data set were calculated using BLUP of the genotypic means within environments. Correlations across genotypes and environments were also calculated using BLUP of means of genotypes and environments, respectively.

A covariate-effect biplot was constructed as described by Yan and Tinker (2005). Correlation coefficients were calculated between test weight and other traits using BLUP value of cultivars in each growing location and year combination. The trait × environment two-way table of correlation coefficients was decomposed into principal components (PC) using singular value decomposition and the biplot was drawn using the first two PC values. Calculation of correlation coefficients and singular value decomposition were performed (v.9.1, SAS Institute, Cary, NC).

RESULTS

Relationships might be expected between test weight and groat proportion, however the crude comparisons of genotypic means of test weight and groat proportion data would suggest that the relationship was a loose one (Table I). The four genotypes with the highest test weight were Beach, CDC Dancer, Ronald, and ND021612, whereas the four genotypes with the highest groat proportion were CDC Dancer, Ronald, CDC Weaver, and AC Pinnacle. The four genotypes with the lowest test weight were Brawn, Leonard, Otana, and AC Morgan. The lowest four genotypes for groat proportion were HiFi, AC Morgan, Otana, and Leonard. Although there was some consistency between the genotypic rankings of test weight and groat proportion, some obvious differences among them reflect differences in the factor affecting these characteristics. Sand displacement analysis of kernel volumes (Table I) indicated the three genotypes with the largest kernels by volume (CDC Weaver, Brawn, and Maida) also had the largest kernels by mass. However, the genotypes with the smallest kernels by volume (Otana, Ronald, and Beach) were different than those three that were smallest by mass (Leonard, HiFi, and Otana). Genotypic mean kernel densities were 0.867–0.982 mg/mm^3 and rankings were more similar to test weight than groat proportion. Packing proportions were 0.511–0.531. Thus, a relatively small range was observed in packing proportion across genotypes when compared with test weight, groat proportion and kernel density.

The four genotypes with the greatest groat mass (CDC Weaver, Brawn, Maida, and AC Assiniboia) were the same as the four with the greatest groat volume (Table II), although their order differed slightly. The smallest three genotypes for groat mass were also the same as for groat volume. Thus, genotypic ranking for groat mass was fairly similar to that of groat volume. This ranking was more similar to kernel mass than kernel volume. Groat density exhibited significant genotypic variation and ranged from 1.043 to 1.124 mg/mm^3.

Genotypic ranking for hull mass (per kernel) was similar to the genotypic rankings for hull volume (Table II). Three genotypes with greatest hull mass (Brawn, Gem, Leonard) were the same as the three with greatest hull volume. Also, three genotypes (Ronald, Beach, CDC Dancer) were among the lowest four for both hull mass and hull volume. Hull density was 0.594–0.709 mg/mm^3. No distinctive patterns to hull density were obvious from the genotypic hull density means.

TABLE I
Genotypic and Environmental Means for Test Weight, Groat Proportion, and Kernel Density Data for 18 Genotypes Grown at Six Environments Estimated from BLUP[a,b]

Genotype	Test Weight (kg/L)	Groat Proportion (-)	Mean Kernel Mass (mg)	Mean Kernel Volume (mm^3)	Mean Kernel Density (mg/mm^3)	Packing Proportion (-)
AC Assiniboia	0.479	0.738	35.9	38.4	0.934	0.516
Beach	0.515	0.738	33.0	33.5	0.982	0.523
Brawn	0.459	0.701	38.0	42.0	0.909	0.511
CDC Dancer	0.509	0.779	33.7	35.5	0.949	0.531
Gem	0.474	0.698	35.3	39.0	0.910	0.522
HiFi	0.486	0.688	32.0	34.4	0.930	0.522
Killdeer	0.478	0.723	32.6	35.8	0.913	0.523
Leonard	0.452	0.669	32.2	37.0	0.878	0.518
Maida	0.492	0.729	36.7	39.0	0.940	0.523
AC Morgan	0.449	0.681	33.1	37.9	0.877	0.516
Morton	0.488	0.692	33.0	35.5	0.928	0.525
ND021612	0.496	0.709	35.6	37.2	0.953	0.520
ND030291	0.482	0.734	32.5	34.7	0.936	0.517
Otana	0.451	0.671	29.5	34.3	0.867	0.522
AC Pinnacle	0.492	0.743	33.6	36.1	0.930	0.527
Ronald	0.503	0.756	32.5	34.0	0.952	0.526
Triple Crown	0.460	0.689	34.4	38.4	0.897	0.516
Weaver	0.485	0.754	40.4	43.4	0.932	0.521
$LSD_{0.05}$	0.019	0.022	1.9	1.7	0.033	0.013
Environment						
Carrington 05	0.488	0.746	36.4	38.9	0.910	0.524
Carrington 06	0.455	0.687	35.0	37.9	0.920	0.495
Fargo 05	0.498	0.767	35.0	37.6	0.908	0.533
Fargo 06	0.495	0.675	33.4	35.3	0.925	0.536
Williston 05	0.481	0.765	32.5	35.7	0.935	0.526
Williston 06	0.466	0.658	32.3	36.8	0.940	0.513
$LSD_{0.05}$	0.013	0.041	2.0	2.5	ns	0.021

[a] Groat proportion and packing proportion are ratios and have no units.
[b] BLUP, best linear unbiased predictor; ns, not significant.

TABLE II
Genotypic and Environmental Means of Oat Groat and Hull Mass, Volume, and Densities of 18 Oat Genotypes Grown at Six Environments Estimated by BLUP[a]

Genotype	Mean Groat Mass (mg)	Mean Groat Volume (mm^3)	Mean Groat Density (mg/mm^3)	Mean Hull Mass (mg)	Mean Hull Volume (mm^3)	Mean Hull Density (mg/mm^3)
AC Assiniboia	27.0	24.9	1.086	8.86	13.5	0.650
Beach	25.3	22.7	1.109	7.80	11.0	0.707
Brawn	27.4	26.4	1.043	10.50	15.5	0.671
CDC Dancer	26.6	24.0	1.108	7.27	11.7	0.626
Gem	25.1	22.2	1.124	10.13	16.6	0.625
HiFi	23.4	21.7	1.076	8.70	12.8	0.674
Killdeer	25.0	23.1	1.083	7.73	12.8	0.606
Leonard	22.1	19.9	1.105	10.06	16.9	0.601
Maida	27.2	25.0	1.086	9.44	14.0	0.670
AC Morgan	23.6	22.7	1.045	9.44	15.2	0.625
Morton	24.0	22.3	1.081	8.94	13.3	0.659
ND021612	26.1	24.3	1.079	9.42	13.0	0.709
ND030291	24.5	22.7	1.089	8.06	12.1	0.659
Otana	21.2	20.2	1.053	8.33	14.1	0.594
AC Pinnacle	25.7	23.5	1.092	7.98	12.7	0.631
Ronald	25.8	23.3	1.104	6.90	10.9	0.612
Triple Crown	25.2	23.5	1.076	9.10	14.9	0.623
Weaver	31.2	29.4	1.070	9.09	14.0	0.646
$LSD_{0.05}$	1.5	1.2	0.027	1.11	1.7	0.062
Environment						
Carrington 05	27.9	25.4	1.080	8.77	13.8	0.632
Carrington 06	24.8	22.9	1.082	10.16	15.0	0.677
Fargo 05	27.3	24.9	1.081	7.95	12.9	0.625
Fargo 06	24.0	22.2	1.083	8.17	12.9	0.638
Williston 05	25.4	23.6	1.086	7.05	12.0	0.590
Williston 06	22.8	21.6	1.090	10.48	15.0	0.700
$LSD_{0.05}$	1.1	1.4	ns	1.39	1.7	0.070

[a] BLUP, best linear unbiased predictor; ns, not significant.

Linear dimensions of kernels are presented (Table III) because of the importance of kernel and groat dimensions to packing and groat proportion. The largest kernels by image area (Weaver and Brawn) are consistent with the largest by length. Also, the smallest genotypes by image area (Pinnacle, Dancer, Beach, Ronald) were also the smallest by length. Oat width less strongly corresponded with patterns shown for oat image area and oat length. Nearly all aspects of kernel and groat linear dimensions were significantly correlated with each other (correlation table not shown). Of particular interest were environmental means. For unknown reasons, kernels from Carrington 2006 were significantly longer than kernels from all other environments (Table III). Groats from this location were also longer than those from most other environments. Grain samples from Carrington 2006 also had the lowest grain packing proportions of any other location (Table I).

Correlation analysis (Table IV) confirmed many of the apparent associations. Test weight, groat proportion, kernel density, and packing proportion were all significantly and positively correlated with each other. All of these characteristics were also negatively and significantly correlated with hull mass, hull volume, oat length, and oat image area. All of these characteristics appear to be interrelated in complex ways. Significant correlations among all characteristics associated with kernel size, including kernel mass, kernel volume, groat mass, groat volume, oat length, oat width, and oat image area reinforce confidence in the size measurements made by a diversity of methods. In an attempt to determine differential contributions of genotypic and environmental effects on the relationships of test weight to groat proportion, kernel density, and packing proportion, separate genotypic and environmental correlations were made (Table V). Correlations calculated across

TABLE III
Genotypic and Environmental Means for Grain and Groat Linear Dimensions as Measured by Digital Image Analysis for 18 Genotypes Grown at Six Environments Estimated from BLUP[a]

	Oat			Groat		
Genotype	Length (mm)	Width (mm)	Image Area (mm^2)	Length (mm)	Width (mm)	Image Area (mm^2)
AC Assiniboia	10.89	2.81	22.68	7.95	2.50	15.13
Beach	9.86	2.76	20.16	7.45	2.46	14.05
Brawn	11.62	2.84	24.41	8.04	2.53	15.77
CDC Dancer	10.05	2.72	20.18	7.87	2.47	14.82
Gem	10.97	2.93	23.77	7.31	2.60	14.40
HiFi	10.56	2.78	21.62	7.82	2.44	14.64
Killdeer	10.61	2.79	21.31	7.65	2.46	14.35
Leonard	10.56	2.84	22.42	7.50	2.46	13.90
Maida	11.15	2.79	22.84	8.05	2.49	15.44
AC Morgan	11.24	2.78	23.08	7.85	2.44	14.47
Morton	10.33	2.83	21.60	7.54	2.50	14.30
ND021612	10.78	2.85	22.70	8.04	2.57	15.60
ND030291	10.52	2.76	21.40	7.97	2.45	14.95
Otana	10.20	2.82	21.41	7.00	2.47	13.10
Pinnacle	9.83	2.82	20.26	7.70	2.49	14.33
Ronald	9.94	2.73	20.03	7.69	2.44	14.37
Triple Crown	10.98	2.84	23.03	7.89	2.52	14.98
Weaver	11.36	2.95	24.86	8.60	2.65	17.52
$LSD_{0.05}$	0.28	0.06	0.65	0.15	0.06	0.56
Environment						
Carrington 05	10.82	2.93	22.92	7.87	2.58	15.36
Carrington 06	11.40	2.86	23.52	7.94	2.51	15.11
Fargo 05	10.21	2.93	21.97	7.69	2.61	15.23
Fargo 06	10.46	2.70	21.11	7.73	2.40	14.22
Williston 05	10.25	2.69	20.65	7.79	2.47	14.69
Williston 06	10.68	2.78	22.41	7.62	2.40	14.10
$LSD_{0.05}$	0.31	0.09	1.01	0.18	0.07	0.68

[a] BLUP, best linear unbiased predictor.

TABLE IV
Correlation Coefficients of Test Weight, Groat Proportion, and Kernel Density Measurements with Physical Kernel Properties[a]

	Test Weight	Groat Proportion	Kernel Mass	Kernel Volume	Kernel Density	Packing Proportion
Groat proportion	0.591**	–	–	–	–	–
Kernel mass	0.141	0.307**	–	–	–	–
Kernel volume	–0.277**	0.059	0.872**	–	–	–
Kernel density	0.771**	0.431**	0.260*	–0.221*	–	–
Packing proportion	0.681**	0.419**	–0.191	–0.289*	0.115	–
Groat mass	0.465**	0.732**	0.822**	0.605**	0.398**	0.190
Groat volume	0.313**	0.643**	0.827**	0.690**	0.278*	0.122
Groat density	0.437**	0.249*	–0.064	–0.306**	0.478**	0.155
Hull mass	–0.574**	–0.689**	0.358**	0.523**	–0.254*	–0.691**
Hull volume	–0.740**	–0.627**	0.253*	0.577**	–0.619**	–0.553**
Hull density	0.063	–0.384**	0.296**	0.092	0.482**	–0.441**
Oat length	–0.609**	–0.389**	0.539**	0.739**	–0.325**	–0.674**
Oat width	–0.061	0.131	0.657**	0.641**	–0.096	–0.208*
Oat image area	–0.516**	–0.297**	0.695**	0.873**	–0.320**	–0.576**
Oat width length ratio	0.580**	0.487**	–0.050	–0.269*	0.278*	0.517**

[a] *, $P < 0.05$; **, $P < 0.01$.

genotypic means for test weight indicated r = 0.955 with kernel density and r = 0.690 with packing proportion. Both of these values were significant, but suggested that across genotypes, kernel density was more important in accounting for variation in test weight. However, across environments, test weight value with packing proportion was r = 0.964, which was significant, whereas, test weight value with kernel density was only r = –0.428 (not significant). Thus, across environments, packing proportion affected test weight much more than kernel density did.

This data set allowed the testing of the theoretical relationships between groat proportion, kernel density, and test weight derived earlier in this report. These are tabulated in Table VI. Groat proportion, as calculated from the ratio of the mean groat mass to the mean kernel mass accounted for 75% of the variation in the GP as measured experimentally and calculated according to equation (15). Kernel density, calculated from equation (13) could account for 76% of the observed variation in KD as measured directly. Test weight, as calculated by equation (14) could account for 83% of the observed variation in test weight. Alternatively, test weight as calculated by equation (6) could account for only 65% of the variation in the directly measured values for test weight. In contrast, R^2 values derived from correlation coefficients in Table IV suggest that groat proportion alone could account for only 34% of the variation in test weight, and kernel density alone could account for 59% of the variation in test weight.

Analysis of variance on variables analyzed in this study as shown in Tables I and II, indicated that test weight, percent groat, mean kernel mass, mean kernel volume, mean kernel density, packing proportion, and mean hull volume exhibited significant genotype × environment interactions (not shown). The interactions appeared to be due to differences in magnitude of differences, rather than differences in direction of responses. The interactions are presumed to be derived from different responses of the genotypes to the various diverse environmental conditions to which the oats were exposed during their culture. The year 2006 was much drier than 2005, and the Williston location was much drier than Carrington and Fargo in both years. Associated with environmental conditions was the incidence of crown rust (incited by *Pucinia coronata* Cda. f. sp. *avenae* Eriks.). In this study, significant crown rust infections were observed only at Carrington and Fargo in 2005. Infection of genotypes is dependent on genetic resistance of cultivars to extant races of crown rust. Thus, we would attribute at least a large proportion of the observed G × E interactions to variations in responses in environmental conditions, especially associated with crown rust resistance.

A covariate-effect biplot (Fig. 1) was generated to visualize the effects of traits on test weight and similarity in response to environmental variations (Yan and Tinker 2005). Most of the variation (96.5%) in test weight could be described by a single axis (PC1), whereas, the second axis (PC2) described only 1.3% of the variation. The characteristics furthest from the center, where test weight is located, had the greatest influence on test weight. Thus, according to the biplot, kernel density (KD) and groat proportion (GP) had the greatest positive influence on test weight, whereas hull volume (HV) and oat kernel length (OL) and area (OA) appeared to have the greatest negative effects on test weight. Specifically, the cosine of the angle between two vector lines of traits measures the similarity in associations with test weights in response to environments (Yan and Tinker 2005). The vector line with groat proportion (GP) showed a small angle with that of kernel density (KD), suggesting that these characteristics had similar effects on test weight. The environments showed similar positive values for PC1 and both positive and negative values for PC2. This result indicated that PC2 was partly responsible for variation due to the environments although it explained only some of the

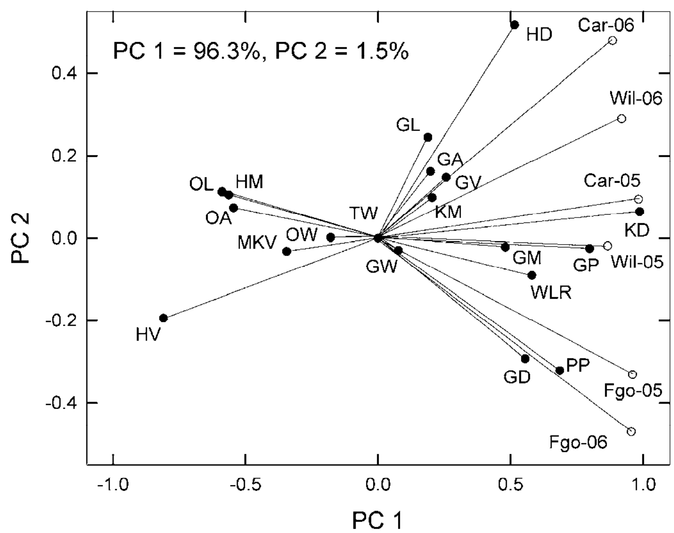

Fig. 1. Covariate-effect biplot of two principal components (PC) calculated from correlation coefficients between traits and test weight among cultivars in each growing location and year combination. Traits in solid circles: GA, groat area; GL, groat length; GP, groat proportion; GW, groat width; GD, mean groat density; GM, mean groat mass; GV, mean groat volume; KD, mean kernel density; KM, mean kernel mass; KV, mean kernel volume; OA, kernel area; OL, kernel length; OW, kernel width; WLR, kernel width/length ratio; PP, packing proportion. Environments (location-year) in open circles: Fgo, Fargo; Car, Carrington; Wil, Williston; 05, 2005; 06, 2006.

TABLE V
Correlation Coefficients of Test Weight with Kernel Density and Packing Proportion Across 18 Genotypes or Across 6 Environments[a]

	Correlation with Test Weight	
Factor	**Across Genotypes**	**Across Environments**
Kernel density	0.955**	–0.428ns
Packing proportion	0.690**	0.964**

[a] **, $P < 0.01$; ns, not significant.

TABLE VI
Effectiveness of Predictive Equation for Groat Proportion, Kernel Density, and Test Weight at Predicting Measured Values

Dependent Variable	Prediction Equation[a]	Eq. No.	R^2
Groat proportion	GP = GM/KM	(2)	0.75
Kernel density	KD = 1/[(GP/GD) + (1 – GP)/HD]	(13)	0.76
Test weight	TW = PP/[(GP/GD) + (1 – GP)/HD]	(14)	0.83
Test weight	TW = (PP × GM)/(GP × KV)	(6)	0.65

[a] GP, groat proportion; GM, mean groat mass; KM, mean kernel mass; KD, mean kernel density; GD, mean groat density; HD, mean hull density; TW, test weight; PP, packing proportion; KV, mean kernel volume.

variations. Kernel density (KD) and groat proportion (GP) had small angles with all of the vector lines of environments, indicating that they strongly affected test weight for all environments. Hull density (HD) had a greater angle with Car-06 than the others, indicating a greater association with test weight among genotypes at the Car-06 environment. Packing proportion (PP) showed an acute angle with Fgo-06, but an obtuse angle with Car-06. These results indicate that variation of test weight was affected mainly by kernel density, groat proportion and hull volume and had inconsistent associations with hull density and packing proportion according to growing environments.

Correlation analysis of monthly weather conditions means with oat kernel physical characteristics (correlation table not shown) indicated very few significant correlations. Only a few significant correlations were of interest. Test weight was negatively and significantly correlated with potential evapotranspiration in May. Groat proportion was negatively and significantly correlated with maximum air temperatures in May and July.

Groat proportion was also positively and significantly correlated with rainfall in June. Mean groat density and mean kernel density were both negatively correlated with potential evaporation in July. Mean groat mass and mean groat volume were positively correlated with June rainfall and negatively correlated with July potential evapotranspiration.

DISCUSSION

The results presented here extend the observations made in an earlier report on oat kernel density from this laboratory (Doehlert and McMullen 2008). Here, we provide kernel density data from a much wider range of genotypes in a wider range of environments, including several marginal environments. Results presented here suggest that overall, 59% of the variation in test weight could be attributed to variation in kernel density, and the remainder would be attributed to variation in packing proportion. However, most variation due to kernel density appears to be genotypic in origin, whereas most environmental variation in test weight would be attributed to packing proportion (Table V). More reliable conclusions can be drawn as data from more environments becomes available.

A wider range of mean kernel densities are described here (0.867–0.982 g/cm^3) than were described previously (Doehlert and McMullen 2008). Among genotypic means at individual environments (data not shown), Beach harvested at Carrington in 2006 had the highest density recorded in this experiment (1.016 g/cm^3). Leonard grown at Williston in 2006 had the lowest recorded density (0.768 g/cm^3). The grand mean of kernel density in this study was 0.923 g/cm^3, which is less than the 0.999 g/cm^3 grand mean observed previously (Doehlert and McMullen 2008). The current study appears to include many genotypes with poorer kernel density potential in our environments and growing conditions in the current study appeared to be less favorable than those in the previous study (Doehlert and McMullen 2008).

This data set has allowed us to test some theoretical relationships between test weight and groat percentage and test weight, as indicated by equations (2), (6), (13), and (14) (Table VI). Perhaps most fundamental to our analyses is the relationship between theoretical groat proportion, as calculated by equation (2) and the value of groat proportion derived from dehulling, calculated from equation (15). The calculated ratio of mean groat mass to mean kernel mass could only account for 75% of the variation in the measured values for groat proportion. It begs the question: Why is there so much difference between these values?

Groat proportion, in theory, is equal to the ratio of the groat mass to the oat kernel mass. However, measured values involve a powerful mechanical stress upon the grains, aspiration to remove lighter hull fragments, and a sorting process to remove grains resistant to dehulling. The grand mean for groat percentage calculated from equation (2) was 0.743 for this data set. The mean value obtained from the mechanical dehulling as calculated by equation (15) was 0.716. Paired *t*-test indicated that these values were significantly different. Several reasons can be postulated for this difference. Some groats may be lost during the aspiration process or may be pulverized during the dehulling process, which would decrease the measured groat percentage relative to the theoretical value. Groats that are broken during the dehulling process are not used for the calculation of mean groat mass, which could bias the mean groat mass value. Also, the mass of kernels resistant to dehulling are subtracted from the starting mass of oats (equation 15). It is likely that kernels resistant to dehulling have lower groat percentage than those that were dehulled in a single pass through the dehuller (Browne et al 2002; Doehlert and Wiessenborn 2007), which could contribute to the divergence of calculated values of groat proportion to the theoretical ones. Although the mechanism for this divergence may not be clear at this point, this difference has been observed in previous studies (Doehlert et al 2006). This difference is attributed to experimental error.

Groat proportion alone could account for only 34% of the variation in test weight. When a theoretical test weight was calculated from groat proportion, packing proportion, mean groat mass, and mean kernel volume, according to equation (6) the resulting values could account for ≈65% of the variation in the measured test weight value (Table VI). It is likely that most of the departure of the theoretical test weight from the actual measured values as estimated by equation (6) can be attributed to divergence in the measured values of groat proportion from that expected according to theory. But substitution of the measured groat proportions values with theoretical values results in a circular statement, where 100% of the variation in test weight was accounted for by the theoretical construction.

Kernel density clearly has an important role in determining test weight, as predicted by equation (1). A major factor affecting kernel density is groat percentage. Groats are nearly twice as dense as hulls (Table II), thus the larger mass proportion of the kernels that is groat, the denser the kernel must be. However, our analyses suggest that groat proportion accounted for only 18% of the variation in kernel density. By including groat density and hull density into a description of groat percentage, according to equation (13), 65% of the variation in kernel density values could be accounted for. The divergence of predicted values from measured values can only be accounted for by experimental error in the determination of mean kernel density, groat proportion, mean groat density, and mean hull density, although exactly how the error might be distributed among these factors is not clear. When we used this description of kernel density for predicting test weight as with equation (14), we accounted for 83% of the variation in test weight (Table VI). We would conclude that the prediction of test weight with either equation (6) or (14) generates satisfactory results, although less error appears associated with equation (14).

A relatively small amount of variation in packing proportion was observed. As observed in our earlier study (Doehlert and McMullen 2008), packing proportion appeared to decrease with kernel length. It is interesting that the packing proportion was lowest at Carrington in 2006. That location also had the longest kernels of any of the locations (Table III). Correlation analysis (Table IV) would suggest that kernel length is the most important factor among those we measured for affecting packing proportion. Also, the oat image area and the oat width-to-length ratio were oat kernel size characteristics that were significantly and negatively correlated with packing proportion. Hull mass and hull volume were also significantly and negatively correlated with packing proportion. We suggest that these values must be related to external kernel structures that impede most efficient packing of kernels.

It is clear that any variation in packing proportion will affect the test weight without affecting groat proportion. Thus, variation in packing proportion can cause divergence between groat proportion and test weight. Another possible divergence of test weight from groat proportion might lie in hull density. We can envisage an oat with a dense hull and a low hull volume. The high density hull may contribute to high test weight, whereas increased mass associated with the hull would contribute to a lower groat percentage. Thus, a dense hull could create an oat with a high test weight but a lower groat percentage. We have not documented any such oat genotype, but its characteristics are consistent with theory.

In this study, we observed significant genotypic variation in groat density, whereas in our earlier study (Doehlert and McMullen, 2008), no such variation was observed. Groat density appeared to have an important effect on kernel density, as evidenced by the significant positive correlation (Table IV). Significant and positive correlations between groat density and both test weight and groat percentage provide evidence that groat density had an influence on these characteristics as well. We speculate that less dense groats may contain air spaces from incomplete grain fill. Such incomplete grain fill may be associated with crown rust infection, or with drought conditions, although our results are not complete enough to test these hypotheses reliably.

Our measurement of hull density in this study was indirect, in that hull mass and volume was derived from kernel mass or volume minus the groat mass or volume. This liberty allowed several potential errors to be introduced into these analyses. As pointed out earlier, not every kernel is dehulled to yield a groat. Thus, characteristics of the groats in the kernels that are not dehulled are not included in the measurement of mean groat characteristics. Also, empty space may occur inside the hulls. This empty space would be assigned to hull volume by our calculation, and thus would result in an overestimation of hull volume. Nevertheless, due to the currently insurmountable problems involved in the direct measurement of hull mass, volume, and density, the indirect approach represented the best alternative. In our earlier study, hull mass per kernel was also measured from the difference in mass between the whole kernels and groats. The earlier study indicated hull mass varied 6.9–9.2 mg/kernel. Our current study, which used a greater range of genotypes and environments, indicated a range of 6.6–10.8 mg/kernel. The greater range of hull mass per kernel appeared to be consistent with the greater range of genotypes used in the current study. Hull density as measured directly by sand displacement in our earlier study was 0.66–0.73 g/cm^3. In our current study, where hull density was estimated from differences between the kernel and groat, hull density values were 0.53–0.73 g/cm^3. The finding of hulls with densities much lower than any of those measured previously supports the hypothesis that some empty space occurred within oat hulls. Empty space within oat hulls would obviously cause a decrease in kernel density and in test weight but would have no effect on groat percentage because groat percentage is based entirely on mass. Thus, empty space within hulls could also cause a divergence between groat percentage and test weight. Very dense hulls could contribute positively to kernel density and test weight. Indeed, a positive correlation was observed in this study between hull density and kernel density (Table IV). However, dense hulls have the potential of detracting from groat percentage, as it could contribute to hull mass. This represents another mechanism by which test weight may diverge from groat proportion. Our results also suggest that hull mass and volume may contribute strongly to packing proportion. In that it represents the outer-most layer of the oat kernel, it ultimately determines the shape of the kernel. Modification of the hull characteristics may eventually allow for test weight improvement and contribute to improved groat proportion as well.

Many studies have indicated correlations between test weight and groat percentage. This study provides more precise analyses of why these characteristics may be related, and what factors can cause these characteristics to diverge from each other.

Experimental results presented here support the theoretical relationships proposed within a margin of experimental error.

LITERATURE CITED

Atkins, R. E. 1943. Factors affecting milling quality in oats. J. Am. Soc. Agron. 35:532-539.

Bartley, B. G., and Weiss, M. G. 1951. Evaluation of physical factors affecting quality of oat varieties from Bond parentage. Agron. J. 43:22-25.

Browne, R. A., White, E. M., and Burke, J. I. 2002. Hullability of oat varieties and its determination using a laboratory dehuller. J. Agric. Sci. 138:185-191.

Doehlert, D. C., and McMullen, M. S. 2001. Optimizing conditions for experimental oat dehulling. Cereal Chem. 78:675-679

Doehlert, D. C., and Wiessenborn, D. P. 2007. Influence of physical grain characteristics on optimal rotor speed during impact dehulling. Cereal Chem. 84:294-300.

Doehlert, D. C., McMullen, M. S., and Baumann, R. R. 1999. Factors affecting groat percentage in oat. Crop Sci. 39:1858-1865.

Doehlert, D. C., McMullen, M. S., Jannink, J.-L., Panigrahi, S., Gu, H., and Riveland, N. R. 2004. Evaluation of oat kernel size uniformity. Crop Sci. 44:1178-1186.

Doehlert, D. C., Jannink, J.-L., and McMullen, M. S. 2006. Oat grain/groat size ratios: A physical basis for test-weight. Cereal Chem. 83:114-118.

Doehlert, D. C., and McMullen, M. S. 2008. Oat grain density measurements by sand displacement and the analysis of physical components of test weight. Cereal Chem. 85:654-659.

Forsberg, R. A., and Reeves, D. L. 1992. Breeding oat cultivars for improved grain quality. Pages 751-775 in Oat Science and Technology. H. G. Marshall and M. E. Sorrells, eds. Am. Soc. Agron.: Madison, WI.

Ganssmann, W., and Vorwerck, K. 1995. Oat milling, processing and storage. Pages 369-408 in: The Oat Crop: Production and Utilization, R. W. Welch, ed. Chapman and Hall: London.

Greig, R. B., and Findlay, W. M. 1907. The milling properties of oats. J. Food Agric. London 14:257-268.

Hall, M. B., Tarr, A. W., and Karopoulos, M. 2003. Using digital imaging to estimate groat per cent and milling yield in oats. J. Cereal Sci. 37: 343-348.

Hoffman, L. A., and Livezey, J. 1987. The U.S. Oats Industry. Agricultural Economic Report 573. USDA, Economic Research Service: Washington, DC.

Hlynka, I., and Bushuk, W. 1959. The weight per bushel. Cereal Sci. Today 4:239-240

Lea, H. 1955. Quality in oats and oat products from the oatmeal and provender miller's point of view. J. Nat. Inst. Agric. Bot. 7:404-410.

Love, H. H., Stanton, T. R., and Craig, W. T. 1925. Improved oat varieties for New York and adjacent states. Circular 353. USDA: Washington, DC.

Peek, J. M., and Poehlman, L. M. 1949. Grain size and hull percentage as factors in the milling quality of oats. Agron. J. 41:462-466.

Pomeranz, Y., Davis, G. D., Stoops, J. L., and Lai, F. S. 1979. Test weight and groat-to-hill ratio in oats. Cereal Foods World 24:600-602.

Stoa, T. E. 1922. Varietal trials with oats in North Dakota. Bull. 164. N.D. Agric. Exp. Stn.: Fargo, ND.

Stoa, T. E., Smith, R. W., and Swallers, C. M. 1936. Oats in North Dakota. Bull. 287. N.D. Agric. Exp. Stn.: Fargo, ND.

Sword, J. 1949. Milling values of oat varieties I. 1946 results. Scot. Agric. 28:137-148.

Symons, S. J., and Fulcher, R. G. 1988. Determination of variation in oat kernel morphology by digital image analysis. J. Cereal Sci. 7:219-228.

USDA. 1988. The Official United States Standards for Grain, Federal Grain Inspection Service. Available online at http://archive.gipsa.usda.gov/reference-library/standards/810oats.pdf. USDA: Washington, DC.

Yamazaki, W. T., and Briggle, L. W. 1969. Components of test weight in wheats. Crop Sci. 9:457-459.

Yan, T., and Tinker, N. A. 2005. An integrated biplot analysis system for displaying interpreting and exploring genotype × environment interactions. Crop Sci. 45:1004-1016.

Zavitz, C. A. 1927. Forty year experiments with grain crops. Bull. 332. Ontario Dept. Agric.: Toronto.

[Received June 13, 2008. Accepted December 16, 2008.]